Autonomous Dynamic Instrument Reconfiguration

Brad Hines, Geoffrey Toon, Jean-Francois Blavier
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91009

Michael Deck
Cleanroom Software Engineering, Inc.
7526 Spring Dr.
Boulder CO 80303-5101

Christian Plaunt
NASA Ames Research Center
Moffett Field, CA 94035-1000

Shirley A. Becker
Florida Institute of Technology
150 West University Blvd.
Melbourne, FL 32901

***Abstract*- Many types of Earth observing missions can benefit from having information systems that allow the mission platform and its instruments to quickly adapt to changing conditions. Such adaptability requires, of course, the ability to make intelligent decisions quickly, and a large number of researchers have been making great strides in this area in recent years.**

This paper discusses the fusion of three distinct information systems technologies for space instrumentation into a single integrated platform: dynamic instrument reconfigurability, hard realtime performance, and the tight integration of an autonomous agent to leverage these capabilities.

The approach to this fusion of capabilities is modeled in some ways after higher organisms, which have an autonomous agent (the brain), high-performance or highly complex components (the circulatory system, for example), and high-level ways of controlling the gross state of the individual subsystems (such as adrenalin, hormones, and endocrine functions).

In essence, in higher organisms, the brain frequently does not make detailed decisions about the operation of individual tissues, but rather uses chemicals to broadly "reconfigure" systems for new modes of operation, without having a detailed knowledge of what that means.

Our new technology weds a hard realtime system with an autonomous agent and a configuration database to allow rapid reconfiguration of mission assets in response to external stimuli. This will enable new kinds of observation scenarios, and the ability to switch rapidly between them, to be built into new missions much more easily.

I. Overview of the Technology

We have developed prototype tools that have the following capabilities, and we are working on demonstration of these capabilities in science testbeds in laboratories at JPL:

- Dynamic instrument (re)configuration from onboard "database" of parameters
- Hard realtime performance for instruments
- Integration with high-level autonomous control

The reconfiguration capability has been developed in the context of a system requiring extremely high realtime performance, as is typical of more and more observing systems, such as systems requiring precision structural control or realtime compensation. We are also demonstrating the integration of advanced autonomy technologies, already developed for flying spacecraft, with this high performance and reconfigurability.

Dynamic reconfiguration provides flexibility to science and engineering teams, reducing mission costs and risks, while the additional integration of autonomy with reconfigurability and high performance will allow instruments to react to events in ways previously not possible, greatly enhancing instrument capabilities for opportunistic observing.

The technology that has been developed is of a generic nature, and is conceived as being reusable by a wide variety of earth observing instruments. One of the major products of this effort is a packaged software product that is tailored for ease of reuse by multiple missions, built around industry standards, including your choice of either the VxWorks or RTAI (a realtime Linux) operating systems, the C++ language, and the CORBA distributed computing standard.

The following sections describe these elements in more detail.

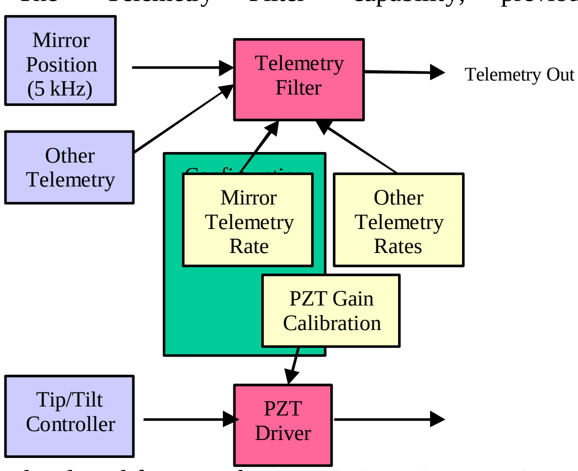
A. *Dynamic Instrument Reconfiguration*

The reconfiguration capability is the most novel element in this technology suite. Even the simplest spaceborne instrument is typically controlled by thousands of parameters. Normally, most of these parameters are hard-coded into the system. Such parameters include:

- The mapping of electronic I/O channels to physical actuators and sensors
- The recording rate of a telemetry item
- The gain of a control loop
- The results of a recent sensor or actuator calibration
- The desired operating mode of a piece of equipment

It is usual for instruments to handle calibration data differently from control loop gains; this new capability places *all* of these parameters in a "configuration database." The result is shown in the figure below. All configuration information is collected in one place. This allows manipulations of the configuration data and enables scenarios of instrument operation that have not heretofore been feasible.

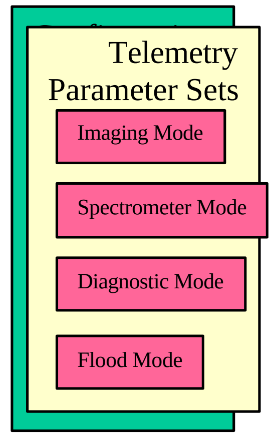
The "Telemetry Filter" capability, previously



PZT (Piezoelectric Transducer)

developed for astrophysics missions, is a case in point. Telemetry transmission is controlled by a configurable filter. Telemetry items can be on, off, periodically sampled, recorded only when a value changes, or sampled with timing controlled by some internal process. Since individual items can be turned on and off, the entire telemetry stream is customizable in real time. Virtually any value in the system can be telemetered without penalty in performance or development effort. We have developed database manipulation techniques that allow maximum use of this flexibility.

Named parameter sets are another capability that has been delivered in the prototype that has been developed. The figure here shows different sets of configuration information for the same telemetry items.



In this example, there are four modes affecting camera telemetry. Imaging mode records the entire field of a 512x512 camera for downlink. Spectrometer mode filters the data to send a single 512-pixel line of the camera data. Diagnostic mode downlinks a specific suspect subwindow of the camera. Flood mode sends full frames at an increased data rate. The entire telemetry system can be told to reconfigure itself using the appropriate named parameter set, very easily allowing any desired telemetry set to be sent. This capability also allows run-time reconfiguration and fine subsetting of the parameter space, as dictated by the needs of the specific instrument.

Object-oriented techniques are used so that each object knows how to reconfigure itself. When a reconfigurable object is created, it stores a path to its configuration information in the database. This information persists so that the object can later be told to reconfigure, possibly specifying an alternative path. Objects are organized hierarchically so that a single reconfigure request includes all affected objects.

For example, reconfiguring the camera component of an imaging subsystem would lead to reconfiguration of all camera parameters, including the camera's operating mode, exposure time, data storage, and dark calibration.

The dynamic nature of the configuration information, together with the versioning capability, makes the configuration database a natural place to store calibration information, even for calibrations that are repeated regularly. For example, for an imaging camera, the database could store an as-launched calibration, a “cloudy day” calibration, a “sunny day” calibration, calibrations for operating at different wavelength bands, etc. On-orbit recalibrations could be performed and put into effect with confidence, knowing that the previous calibrations are still available if needed.

B. Hard Realtime Performance

For years, hard realtime performance (deterministic system response of 0.1 ms or less) has conflicted with the goals of developing a structured software system. When 10 kHz sampling loops were needed, electronics engineers developed dedicated signal processing hardware for the task. This led to rigid interfaces and the inability to easily upgrade the device or to modify the task it performs.

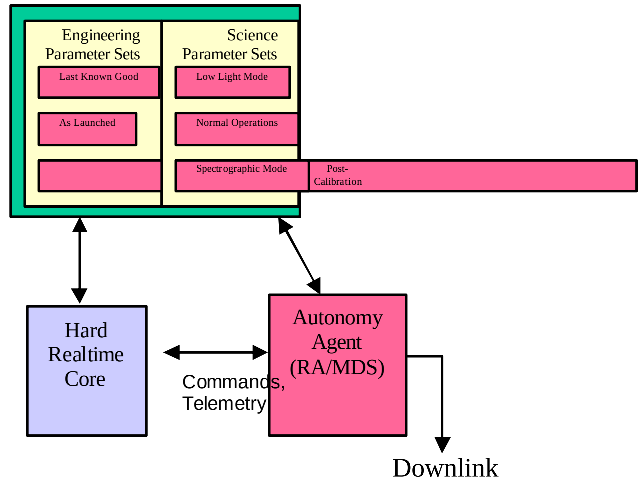
Today, spaceworthy general-purpose processors are fast enough to handle these kinds of demands, if the software is carefully constructed. We have developed a realtime control toolkit that supports tight integration with the other technologies presented here [1]. This allows developers to quickly create hard realtime applications for systems requiring hard realtime performance, while getting features such as telemetry, commanding, and reconfigurability "for free". These kinds of realtime demands appear in systems that require high-speed control loops, such as adaptive optics systems and controlled structures. These and similar technologies are an integral part of current and future earth observing plans. Enabling hard realtime performance with a general-purpose operating system allows elimination of the costs and risks of dedicated signal processor development.

C. Integration with Autonomous Control

Autonomous agents are becoming proven space technologies. Deep Space 1’s Remote Agent (RA) technology [2, 3], and newer systems like JPL’s Mission Data System (MDS) provide capabilities that enable sophisticated behavior from spacecraft systems. Second generation toolsets are now becoming available. Today, the challenge of autonomous systems is to make effective use of the packages that are available, and to find ways to use autonomy to leverage and enhance other technologies.

The dynamic reconfiguration capability achieves its greatest utility when married to an overseeing autonomous agent. We are using the second generation toolset from Ames Research Center, known as IDEA [4]. As we complete final integration with the agent, it will make decisions about when data is suitable for storage in the configuration database and when instrument systems should be reconfigured.

The figure below shows how the three major technology components are integrated. A hard realtime core gets its configuration from the configuration database and communicates with an autonomous agent. The agent monitors telemetry from the realtime core and controls its behavior via commands.



Here is a sample operating scenario. The realtime system performs a dark current calibration on an imaging sensor. The autonomous agent notes that a new calibration is available, commands that it be stored in the configuration database, and then instructs the pertinent elements of the realtime system to reconfigure themselves as appropriate.

Now, suppose that there was a cosmic ray hit or an unexpected glint during dark calibration that resulted in suboptimal performance. The autonomous agent, observing science products produced by the imaging system, notices that the data quality metric has fallen consistently short of desired levels since the new calibration went into effect. It can then revert to the old calibration and resume operations, thus minimizing data loss. Later, when the mission timeline permits, the agent can command a new recalibration. Repeated recalibration failures would indicate a more serious problem.

The autonomous agent allows the system to access the full power of the dynamic reconfiguration capability. In the technology described here, we are integrating the second-generation IDEA agent with the other components in order to demonstrate the kinds of complex behaviors discussed.

D. Background

This work has extended software, previously developed for JPL's stellar astronomical interferometry program, to support Earth Observing missions. The previously developed software, known as the "RTC Core" (Real Time Control Core), provides the hard realtime performance capabilities needed by all of JPL's stellar interferometer missions. These include testbeds for the Space Interferometry Mission as well as the ground-based Keck Interferometer.

The RTC Core software is a design focused on reliable operation in a multi-processor environment. It combines a general real-time information processing system with an interferometry-capable package. The RTC Core package includes intelligent sensor control, hooks for autonomy integration, and high-speed control capability (supporting loop rates of 10 kHz or more on general-purpose CPUs). The RTC Core package is already highly configurable in nature, with many of its command, control, and telemetry subunits accessible through CORBA interfaces. RTC Core is now approaching maturity and is already in use in a number of systems at JPL and elsewhere.

II. SCIENCE TESTBEDS

We are delivering this new technology into two science application testbeds, one targeting an FTIR spectrometer, and one targeting a Doppler lidar. We will briefly describe each application.

A. Fourier Transform Infrared (FTIR) Spectrometer

Although most current atmospheric research focuses on the stratosphere, particularly ozone, scientific focus is shifting to the troposphere, particularly the global response of the atmosphere to regional pollution (including greenhouse gas emission). [5, 6, 7]

The troposphere represents a formidable challenge for atmospheric remote sounding instruments, as measured radiances are unpredictable and vary greatly, especially for limb sounding techniques, in which the atmosphere is viewed in a direction tangential to the surface; recent experiments (e.g. HALOE, CLAES, ATMOS) have experienced difficulties in extending their measurements down into the troposphere. These difficulties are not fundamental, but are a result of these instruments' inability to adapt to the highly variable character of the tropospheric radiance, or to maintain adequate pointing in the presence of large radiance gradients.

Future science results can be enhanced by using the proposed technology in two ways: (i) adapt and re-optimize the instrument in realtime to maintain data quality, (ii) maintain good knowledge of instrument pointing and where the measured radiation is coming from.

An autonomous agent coupled with a reconfiguration capability has the ability to rapidly modify FTIR instrument parameters in response to perceived problems or opportunities. Some specific examples of possible benefits of this approach are:

- A thermal emission FTIR spectrometer, upon sensing that the limb path is completely opaque, would abort the current limb scan sequence, search in azimuth for a location where the limb path is more transparent, and then take a limb sequence there.
- The ability to monitor and control peak interferogram amplitude, which varies due to variations in cloud or gaseous absorption, by controlling the gain of the signal chain, thus maintaining maximum SNR in the presence of varying signal levels, an enhancement over existing instruments. Similarly, the path difference over which the interferogram is scanned could be optimized in realtime, resulting in increased instrument efficiency.
- An FTIR spectrometer designed for solar occultation could also perform lunar occultations. Reconfigurable parameters sets would allow radically different scenarios (moon vs. sun) of pointing control, signal chain gains, thermal control, power management, and coordination of observing and spacecraft pointing activities.

Reconfigurability would also allow opportunistic observing of exciting events. In 1991, following the Pinatubo eruption, which filled the lower stratosphere up to 20 km altitude with volcanic aerosol for several months, substantial data degradation and lost science resulted due to the inability of atmospheric remote sensing instruments to adjust their gains and tracking methods.

Other FTIR instrument parameters can be enhanced by a hard realtime capability. For example, improved sun tracking performance would allow quicker acquisition at sunrise, avoiding loss of data in the lowest few km of each sunrise occultation, and autonomous capability would allow the system to "learn" the apparent position and variation in shape of the sun during cloud-free sunsets, allowing improved data quality for subsequent sunrises.

Our FTIR testbed is specifically targeted at developing improved performance for the FTIR's Sun tracker, in order to improve spectral and altitude resolution for the FTIR instrument as a whole, and in order to extend it to be able to use targets other than the Sun. This requires coordination of a hard realtime tracker element with the ability to rapidly reconfigure hardware and software elements for Sun/Moon/stars, and changing weather conditions. This new technology is enabling new explorations into tracking algorithm tuning based on the details of individual scans.

B. Doppler Lidar

Doppler lidar tropospheric wind profilometry has been identified as a critical measurement capability for investigation of the global water and energy cycle, and for global change research. One technique for acquiring global 3-D maps of the tropospheric wind field from Earth orbit is Doppler lidar. Both coherent and incoherent lidar approaches to this problem face challenges in the areas of quasi-autonomous instrument management and real-time performance optimization [8].

The dynamic range of lidar returns from the Earth's atmosphere and surface is very wide.[1] An autonomous agent monitoring the incoming data stream could make real-time adjustments to receiver gain to optimize use of the available dynamic range, greatly benefitting the global wind measurement application. The agent, coupled with a realtime control capability, could also on this basis implement "shot-management" of the lidar, varying the transmitter pulse repetition frequency, pulse accumulation in the signal processor, and scan pattern strategy and implementation in order to optimize signal-to-noise ratio and scientific value, while conserving instrument life.

Additionally, and especially in the case of the coherent lidar option, instrument performance is critically dependent on maintenance of system optical alignment [9]. Many factors interact in complex ways[2] to degrade science data quality and instrument reliability. The new technology that has been developed can coordinate automated alignment, understand intrinsic and extrinsic environmental conditions, and switch between available parameter sets and instrument configurations in response, and can greatly enhance the capability and lifetime of lidar missions.

A laboratory demonstration is being developed which specifically targets improvement of the signal-to-noise ratio of the lidar return by developing a high-speed frequency tracker. By rapidly tracking the Doppler return frequency, we can keep the overall bandwidth of the analog stages lower, reducing the amount of noise that makes it into the system.

A second effort is aimed at cloud hole detection [10]. Clouds cause loss of science, but most cloud banks sport holes that an intelligent system could steer the lidar shots through, thus reducing wasted shots to only a few percent. The intelligent system can have the capability to switch between hole detection algorithms, reconfigure instrument light levels, repoint the lidar, and so on. Like the FTIR Sun Tracker, this is a case where the developed technology is pushing the development of algorithms to support capabilities not previously conceived of.

[1] There are echoes from the land and ocean interfaces and entrained clouds, as well as the comparatively weaker returns that originate from the aerosol distributions suspended in the atmosphere.

[2] Including transmit/receive alignment degradation due to thermal drift, laser pointing drift, tilt, decenter, or defocus of optical components, etc., and extrinsic factors such as the interaction of Earth orbit motion and scanner motion (necessitating lag-angle compensation).

References

[1] Hines, B., R. Johnson, K. Starr, "Common interferometer control systems architecture," *Proc. SPIE: Astronomical Interferometry* 3350, pp. 644-653 (1998).

[2] Muscettola N., P. Nayak, B. Pell, and B. Williams, "Remote Agent: To Boldly Go Where No AI System Has Gone Before", Artificial Intelligence 103(1-2): 5-48, August 1998.

[3] Bernard, D., Gamble, E., Rouquette, N., Smith, B. Tung, Y., Muscettola, N., Dorias, G., Kanefsky, B., Kurien, J., Millar, W., Nayak, P., Rajan, K., and Taylor, W., "Remote Agent Experiment
DS1 Technology Validation Report",
http://nmp-techval-reports.jpl.nasa.gov/DS1/Remote_Integrated_Report.pdf

[4] Nicola Muscettola, Gregory Dorais, Charles Fry, Richard Levinson, Christian Plaunt, "IDEA: Planning at the Core of Autonomous Reactive Agents", Workshop on On-line Planning and Scheduling, Sixth International Conference on AI Planning and Scheduling, Toulouse, France, 2002.

[5] Farmer, C. B., "High Resolution Infrared Spectroscopy of the Sun and the Earth's Atmosphere from Space," Mikrochim. Acta [Wien], III, 189-214, 1987.

[6] Toon, G. C., "The JPL MkIV Interferometer", Opt. Photonics News, 2, 19-21, 1991.

[7] Persky, M.J., "A Review of Spaceborne Infrared Fourier-Transform Spectrometers for Remote Sensing", Review of Scientific Instruments 66 (10): 4763-4797, October 1995.

[8] G.D. Spiers and M.J. Kavaya, "Considerations for designing a space based coherent Doppler lidar", Proc. 10th Coherent Laser Radar Conf., Mt. Hood, USA, pp 302-305 , June 28 - July 2 ,1999.

[9] Emmitt, G.D., T. Miller and G.D. Spiers, "Pointing knowledge for SPARCLE and space-based Doppler wind lidars in general", Proc. 10th Coherent Laser Radar Conf., Mt. Hood, USA, pp 182-186 , June 28 - July 2 ,1999.

[10] Spiers, G.D., "Space based lidar shot pattern strategies for small targets such as streams", Proc. 11th Coherent Laser Radar Conf., Malvern, UK, pp 3-6, July 2001.